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Cyclic Loading Experiment for Characterizing Foam Viscoelastic Behavior

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ABSTRACT

Several open-cell flexible foams, including aged polyurethane foams, were mechanically characterized over a temperature range of -40 to 20 °C. Compression was performed to obtain the stress-strain behavior of the foams. The stress-strain relation is nonlinear, but typically there is a small range of linear behavior initially. Compressive cyclic loading at different amplitudes and frequencies of interest (20 – 60 Hz) were applied to measure foam's hysteresis properties, i.e. stiffness and energy dissipation. The cyclic characterization includes foams with different amount of pre-strains, some are beyond the initial linear range as occurred in many applications. Commercial available foams TF5070-10, 12, and 15 [1] are included in this study.

Keywords: flexible foam, viscoelasticity, nonlinear viscoelasticity, pre-strain, soft materials, TF5070-10

INTRODUCTION

Flexible foams are used in packaging applications for shock and vibration isolation during shipping and transportation. A common scenario is that the foam component deforms slowly to support the weight of the object when packing. During the transporting environment, the package will be subjected to dynamic load, for example from bumpiness of the road. The loading is vibratory in nature and its amplitude is typically low. The loading profile is known or can be measured. Some critical engineering questions about the packing are: what are the resonance frequencies and how much force is transmitted through the foam to the object? The foam's behavior is known to be very complex. Modeling and analyzing the problem using non-linear viscoelastic analysis is very challenging. To circumvent this difficulty, the foam can be considered to be undergoing a small amplitude vibration superposed onto a larger compression [2]. The analysis can be simplified by approximating the foam behavior to be linear over the small amplitude of strain of interest; therefore, only linear analysis is needed to analyze this small amplitude vibration problem. The approximated linear viscoelastic properties of the pre-stressed foam, however, need to be characterized experimentally before a validated flexible foam model is developed. This paper presents the experiments performed to obtain linear viscoelastic parameters of several flexible foams at various frequencies, temperatures, and pre-strains.

FOAM'S NONLINEAR VISCOELASTIC BEHAVIOR

Figure 1 shows typical compressive stress-strain behaviors of a flexible open-cell foam TF5070-10, which is 10 pcf (pound per cubic foot, lb/ft^3), at different strain rates 0.1, 100, and 200 s^{-1}. The constant strain rate stress-strain curve is generally nonlinear. The loading portion shows typical elastomeric foam behavior with three regimes of initial linear elasticity, elastic-buckling plateau, and densification [3]. Young's modulus E (the initial slope of the curve) and the buckling stress (the boundary separates the linear elastic regime from that of elastic buckling) are clearly rate dependent; the values of E and σ_{el} at 200 s^{-1} are about quintuple and double, respectively, of those at 0.1 s^{-1}. During unloading, it exhibits a strong hysteresis behavior. When the stress returns to zero, the strain lags behind but eventually goes back to zero with little permanent deformation and damage.

Other factors are also known to have significant influences on foam properties such as density and temperature. Figure 2 shows the stress-strain curves of foams of two different densities compressed at the same strain rate 0.1 s^{-1}. The yield stress increases almost 100% when the density changes from 10 to 12 pcf, only a 20% increase. Figure 3 shows the effect of temperature on TF5070-12 (12 pcf) under constant strain rate 0.1 s^{-1}. Notice the vertical axis is in logarithm scale. A flexible foam is generally in rubbery state at the room temperature, where E and σ_{el} change slowly with temperature. When it gets close to the glass transition temperature, a small change in temperature or strain rate may cause those values to change substantially. Modeling the complex nonlinear viscoelastic foam behavior over a wide range of temperature, strain and strain rate is very challenging.

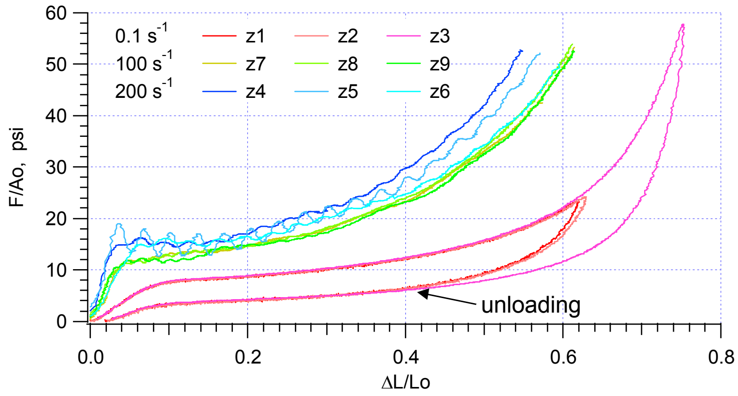


Fig. 1 Compressive stress-strain curves of TF5070-10 foam.at various strain rates.

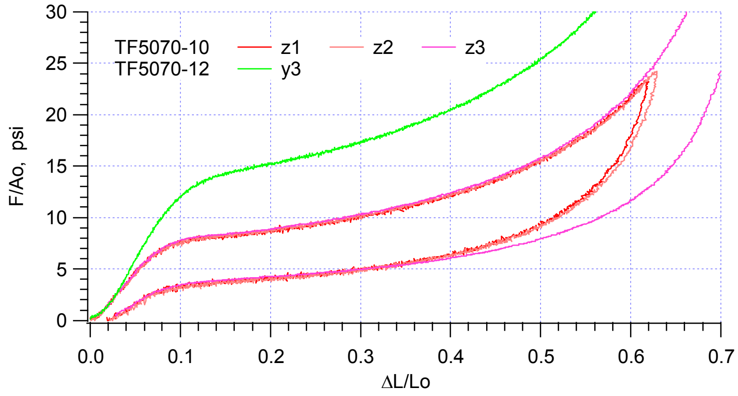


Fig. 2 For TF5070 foams, the crush stress increases almost 100% when density changes from 10 to 12 pcf.

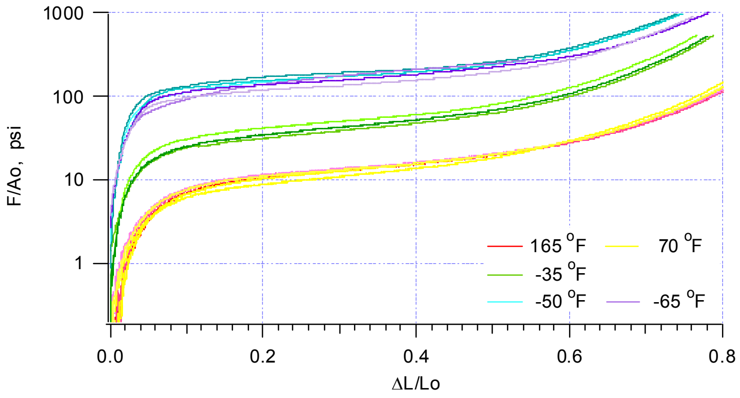
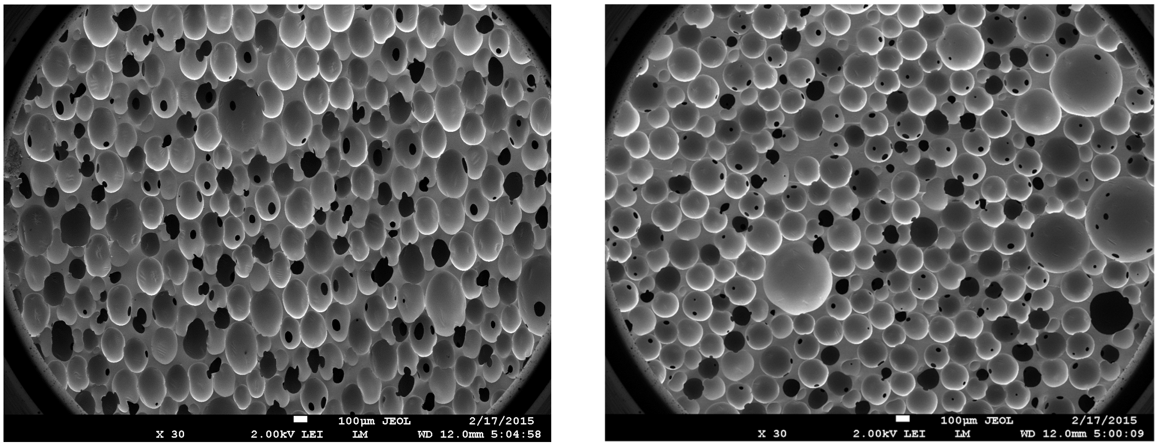


Fig. 3 The crush stress could increase more than 10 times at -65^{o}F comparing to the ambient condition

MATERIAL AND SPECIMEN

Two foam materials were considered in this study: new and aged 15 pcf open-cell flexible polyurethane foams. The new foam was recently purchased; the aged foam was taken from an old block, which was about 30 years old. Figure 4 shows scanning electron microscope (SEM) images of these foams. The averaged cell size is about the same 200 μm (0.008 in). The shape of the cell is slightly different; the new foam's is oval. The foam specimens were cylindrical, the diameter was 10 mm and the length was also 10 mm. The relation between the foam rising direction and the specimen orientation is not known.



(a) (b)

Fig. 3 SEM images of 15 pcf foams: (a) new and (b) aged.

EXPERIMENTAL SETUP

The dynamic compression setup is shown in Fig. 4. It was based on a Bose Bench Top Testing System with an environmental chamber. The load cell was mounted outside the chamber. Extended rods from actuator and load cell were utilized to position the foam specimen in the chamber.

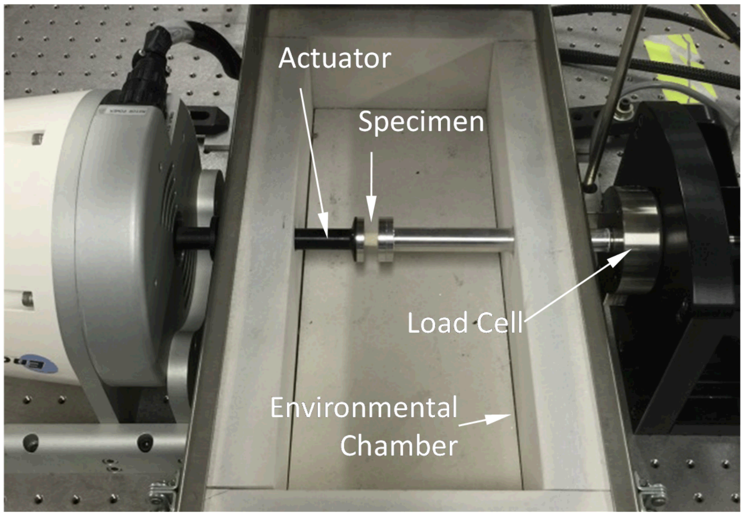


Fig. 4 Foam dynamic compression experimental setup

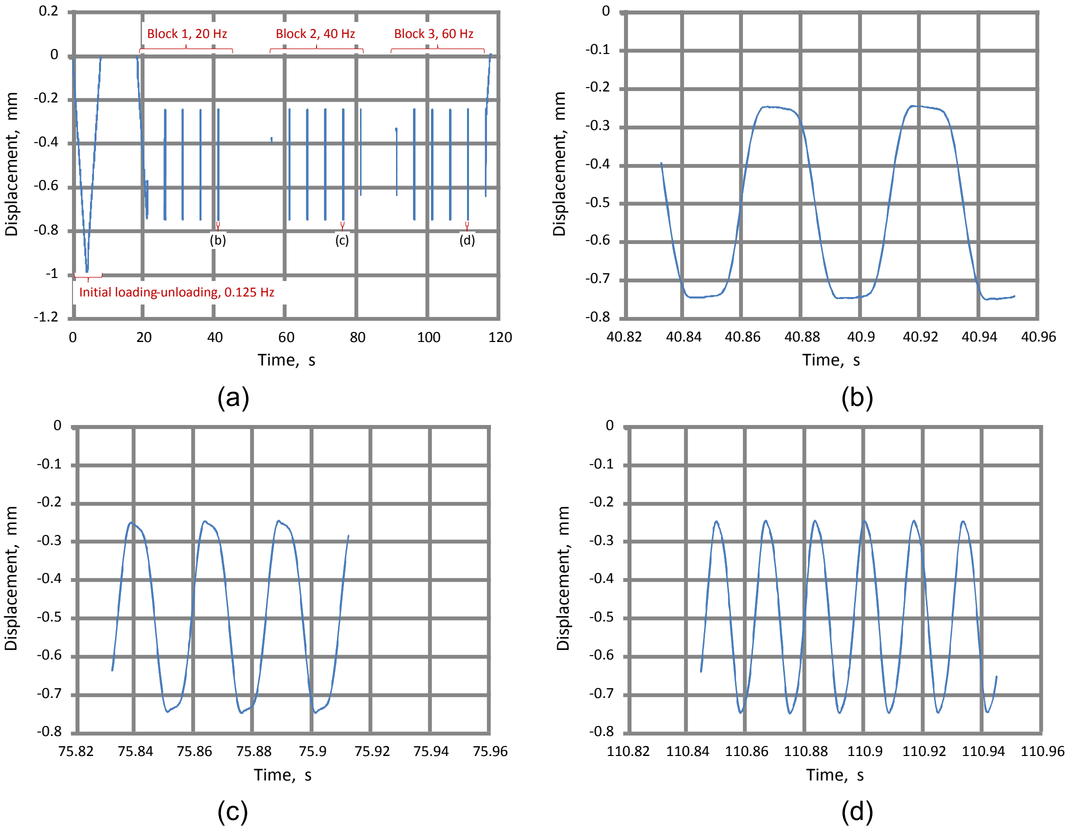
EXPERIMENT

For this series of compression cyclic test, the intension was to obtain the foam viscoelastic properties within the initial elastic regime. A summary of the tests is listed in Table 1. Each specimen was tested under several constant temperature conditions, possibly, 20, 0, -20, -40 ^{o}C. At each temperature, the specimen was subjected to three cyclic loading blocks, which were identified by its distinctive loading frequency, in the following order: 20, 40, and 60 Hz. Each loading block contained at least several hundred cycles of deformation, so the load-displacement hysteresis loop was stabilized. All tests were started with the room temperature condition, 20 ^{o}C. After completing three blocks of loading, the specimen was cooled down to the next temperature level, a step of -20 ^{o}C; and then the three blocks loading was repeated.

In general, the data acquisition rate needs to be at least twenty times faster than the cyclic frequency to characterize the dynamic response. Continuous recording would end up with huge amount of unnecessary data. Here, data was acquired only at selected time periods, approximately a period of 0.1 second for every 5 second. The sampling frequency was greater than 1,000 Hz.

Table 1 Summary of foam cyclic experiments

Sample	Temperature, C				Frequency, Hz				Range
	20	0	-20	-40	1	20	40	60	mm
New03	x	x	x			x	x	x	0.25 - 0.75
New04	x	x	x	x		x	x	x	0.4 - 0.6
New05	x	x	x	x	x	x	x	x	vary
Aged05	x	x	x			x	x	x	vary
Aged06	x	x	x	x		x	x	x	vary



(a) (b)

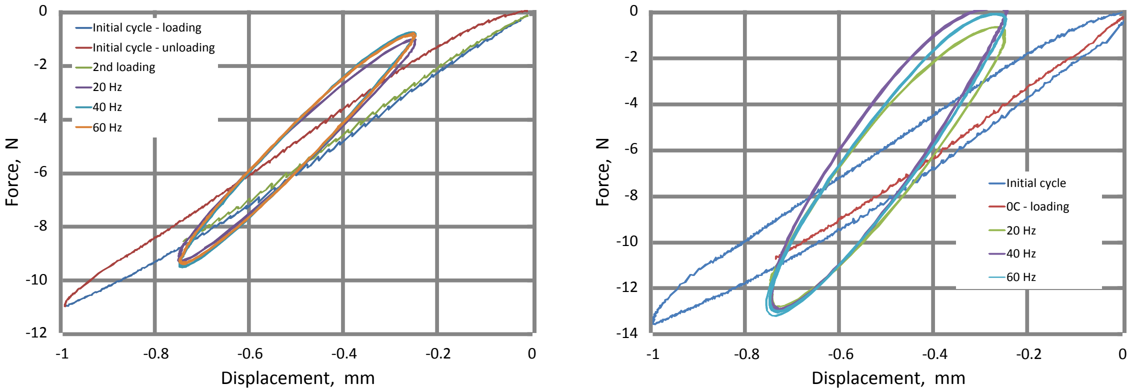
(c) (d)

Fig. 5 Deformation history of New03 at room temperature.

Figure 5(a) displays the deformation history of specimen New03 at room temperature, where only the recorded data are shown. The initial loading-unloading cycle was done at a strain rate of 0.025 s^{-1} with the purpose of verifying that the boundary of the initial elastic regime is about 10%. (Detailed compression properties of 15 pcf polyurethane foams are presented in reference [4].) Three blocks of cyclic loading are indicated on the plot, where the displacement of the actuator traveled between -0.50±0.25 mm, corresponding to -5.0±2.5% strain. The figure does not show cyclic displacement-time curve clearly because of the time scale. Three marked segments are replotted in Fig. 5(b)-(d) with the extended time scale. The averaged strain rates of 20, 40 and 60 Hz loading were about 2.0, 4.0 and 6.0 s^{-1}, respectively, which were about two orders of magnitude higher than the initial cycle. The force-displacement response is plotted in Fig. 6(a). The block cyclic loading was all within the initial linear regime and the stable hysteresis loops are quite similar.

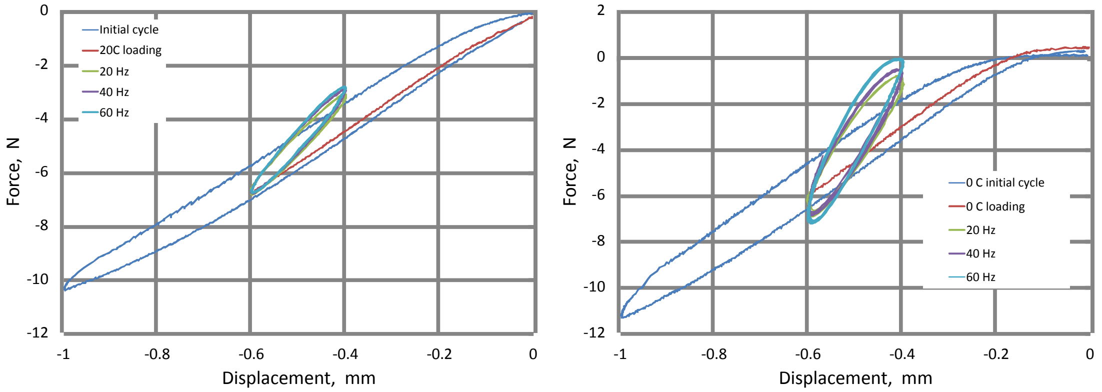
The 0°C response of Specimen New03, with the same pre-strain ε_o = -5% and cyclic strain amplitude $\Delta\varepsilon$ = 5% as in 20°C test, is shown in Figure 6(b). The hysteresis loop of 0°C test is clearly larger than that of 20°C. The 40 Hz hysteresis loop is somewhat distorted at force equals zero, indicating the foam specimen was separated from the platen when displacement was close d = -0.25 mm.

An adjustment of the displacement to -0.50±0.10 mm was applied to foam specimen New04. The results are shown in Fig. 7. With a smaller displacement amplitude, the specimen was always in contact with the platen during cyclic tests at both 20 and 0°C. The room temperature results are shown in Fig. 7(a). The desired pre-strain was ε_o = -5.0% and the amplitude of strain cycle was $\Delta\varepsilon$ = 2.0% (i.e., ±1.0%). Figure 7(b) shows the 0°C results. From the data, the initial loading was delayed after a displacement offset of -0.15 mm, which lead to the pre-strain value of the cyclic test was actually -3.5%, not -5.0%. It is because of changing the temperature environment, difficult to know the amount of displacement offset beforehand, and to control the pre-strain accurately.



(a) (b)

Fig. 6 Stable hysteresis loops, -0.50±0.25 mm, of foam specimen New03 at (a) 20 °C and (b) 0 °C.



(a) (b)

Fig. 7 Stable hysteresis loops, -0.50±0.10 mm, of foam specimen New04 at (a) 20°C and (b) 0°C.

If the material is linear viscoelastic, dynamic characterization could be done at any pre-strain and strain amplitude and the result will be the same. To characterize the initial viscoelastic regime, the only requirement is that the stress should not exceed the buckling stress and the condition of fixed pre-strain and strain amplitude could be relaxed, which made the characterization experiment easier. Figures 8 and 9 show the dynamic characterizations of Specimen New05, Aged05, and Aged06. In these tests, both ε_o and $\Delta\varepsilon$ were varied case by case. Also, to compensate the distance change due to different temperatures, both actuator displacement and crosshead motion were applied; therefore, the displacement between cyclic blocks did not represent the actual actuator displacement.

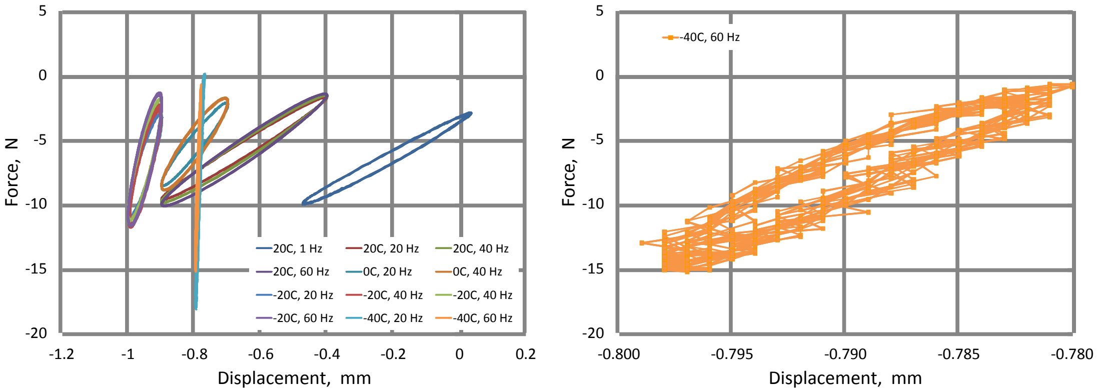
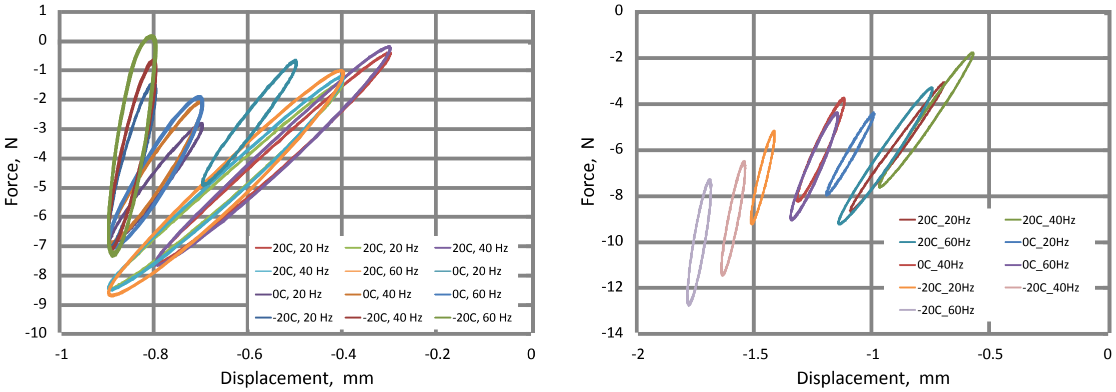


Fig. 7 Stable hysteresis loops of new foam specimen New05.



(a) (b)

Fig. 8 Stable hysteresis loops of aged foam specimen (a) Aged05 and (b) Aged06.

VISCOELASTIC PROPERTIES OF THE INITIAL LINEAR REGIME

For linear viscoelastic material, when cyclic loading reaches equilibrium (i.e., the stress-strain hysteresis loop is stabilized), the stress and strain are sinusoidal but the strain lags behind the stress with a phase difference:

$$\varepsilon = \varepsilon_o + \varepsilon_A \sin(\omega t + \phi_1), \quad \sigma = \sigma_o + \sigma_A \sin(\omega t + \phi_2), \quad \delta = \phi_2 - \phi_1 \tag{1}$$

where ω is the angular frequency and δ is the phase lag. The material's storage and loss modulus, $E1$ and $E2$, can be calculated by

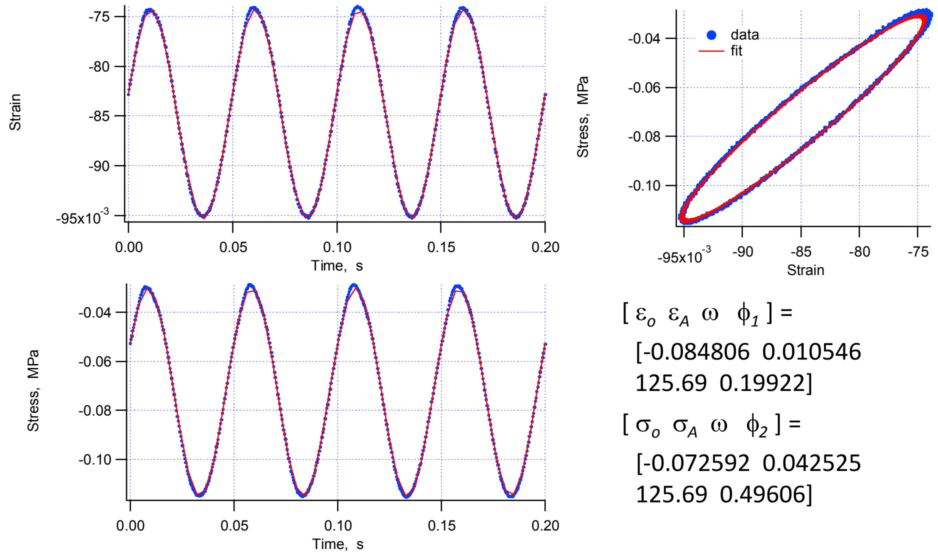
$$E1 = (\sigma_A / \varepsilon_A) \cos\delta, \quad E2 = (\sigma_A / \varepsilon_A) \sin\delta \tag{2}$$

Take the 20 Hz data of Specimen New05 that was tested at 0°C for example, the analysis is shown in Fig. 9. The sinusoidal functions that best fit the strain and stress data are:

$$\varepsilon = -0.084806 + 0.010546 \sin(125.69\, t + 0.19922)$$
$$\sigma = -0.072592 + 0.042525 \sin(125.69\, t + 0.49606) \text{ MPa} \qquad (3)$$

The strain phase lag is

$$\delta = 0.49606 - 0.19922 = 0.29684 \text{ rad} \qquad (4)$$



$[\varepsilon_o\ \varepsilon_A\ \omega\ \phi_1] =$
$[-0.084806\ 0.010546\ 125.69\ 0.19922]$

$[\sigma_o\ \sigma_A\ \omega\ \phi_2] =$
$[-0.072592\ 0.042525\ 125.69\ 0.49606]$

Fig. 9 Viscoelastic data analysis of test New05, 0°C, 20 Hz.

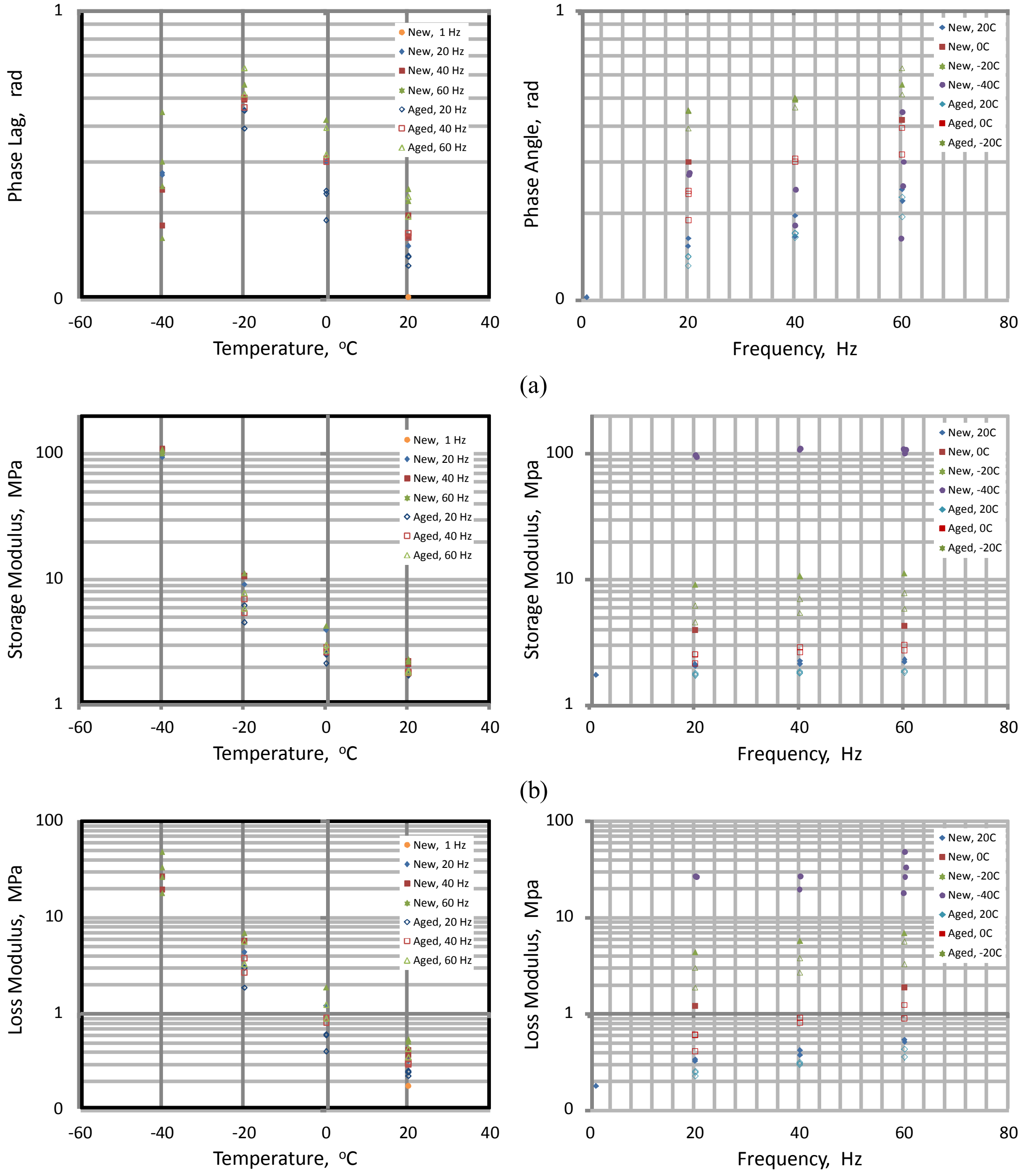
Table 2 Viscoelastic parameters calculated from experimental data

Specimen	Temp	Freq	δ	*E1*	*E2*
	C	Hz	rad	MPa	MPa
New04	20	20	0.15	2.06	0.32
	20	40	0.16	2.20	0.36
	20	60	0.22	2.26	0.50
New05	20	1	0.10	1.70	0.17
	20	20	0.16	2.00	0.33
	20	40	0.19	2.08	0.41
	20	60	0.24	2.16	0.52
	0	20	0.30	3.86	1.18
	0	60	0.42	4.16	1.83
	-20	20	0.45	8.90	4.25
	-20	40	0.49	10.48	5.55
	-20	40	0.49	10.29	5.51
	-20	60	0.55	10.93	6.69
	-40	20	0.27	91.96	25.65
	-40	20	0.27	94.89	26.00
	-40	40	0.24	107.09	25.98
	-40	40	0.18	104.85	18.95
	-40	60	0.30	104.65	32.02
	-40	60	0.44	98.13	46.35
	-40	60	0.16	106.35	17.31
	-40	60	0.24	102.58	25.58
Aged05	20	20	0.13	1.68	0.22
	20	40	0.16	1.77	0.29
	20	60	0.19	1.78	0.35
	0	20	0.19	2.10	0.40
	0	40	0.30	2.58	0.79
	0	60	0.32	2.67	0.87
	-20	20	0.39	4.44	1.81
	-20	40	0.46	5.27	2.60
	-20	60	0.51	5.70	3.17
Aged06	20	20	0.14	1.71	0.24
	20	20	0.14	1.75	0.25
	20	40	0.17	1.80	0.31
	20	40	0.17	1.76	0.30
	20	60	0.22	1.83	0.42
	0	20	0.24	2.46	0.59
	0	20	0.23	2.48	0.58
	0	40	0.31	2.81	0.88
	0	60	0.39	2.93	1.20
	-20	20	0.45	6.05	2.90
	-20	40	0.49	6.83	3.68
	-20	60	0.63	7.61	5.50

The storage and loss modulus are

$$\begin{aligned} E1 &= (0.042525/0.010546)\cos(0.29684) = 3.856 \text{ MPa}, \\ E2 &= (0.042525/0.010546)\sin(0.29684) = 1.1795 \text{ MPa} \end{aligned} \tag{5}$$

The calculated values of δ, *E1*, and *E2* are listed in Table 2. The effects of temperature and frequency on these parameters are shown in Fig. 10. For the temperatures tested, the largest phase lag occurs at -20°C; both storage and loss moduli increase rapidly as the temperature decreases. All these parameters show increase in value as the frequency become higher. Comparing the new and the aged specimens, in general, the values are lower for the aged foam.



(a)

(b)

(c)

Fig. 10 Temperature and frequency effects on (a) phase angle, (b) storage modulus, and (c) loss modulus.

PRE-STRAIN BEYOND THE LINEAR VISCOELASTIC REGIME

Considering 20 Hz, 1.0% strain amplitude loading profile, and various pre-strains beyond the linear elastic regime, initial dynamic characterization of the new and aged foams was done at room temperature. Three pre-strains for new foam specimen test were -13.9%, -29.5%, and -45.6%; three for aged foam were -15.0%, 30.9%, and 47.5%. The stress-strain behaviors are plotted in Fig. 11. More investigation is needed.

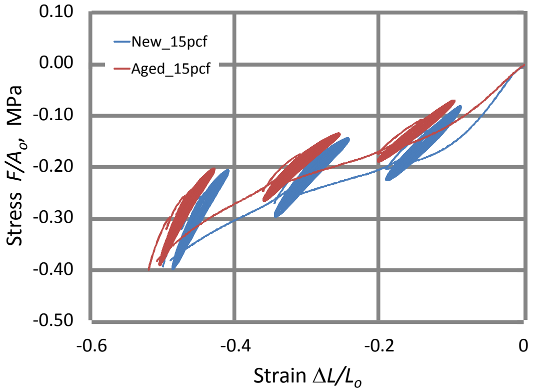


Fig. 11 Stress-strain curves and stable hysteresis loops of new and aged 15 pcf foams.

CONCLUSION

Dynamic characterization of the initial linear viscoelastic regime of the new and aged 15 pcf flexible polyurethane foams were performed. The effects of temperature and loading frequency on storage and loss moduli are obtained. Data show that foams become stiffer and dissipate more energy at lower temperature and higher frequency. Since the aged and new foam specimens were from different batches and many other factors could influence the material property, e.g. density, cell structure, orientation, etc., the observed differences between these two foams should not be interpreted as an aging effect.

The uncertainties increase at low temperatures (< -40^{o}C) and high frequencies (> 40 Hz) for the current setup due to the low load capacity and temperature stability.

Preliminary cyclic experiments of specimens with large pre-strain were studied. More investigation is underway.

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